(54) Title: METHOD AND APPARATUS FOR THREE-DIMENSIONAL SPECTRALLY ENCODED IMAGING
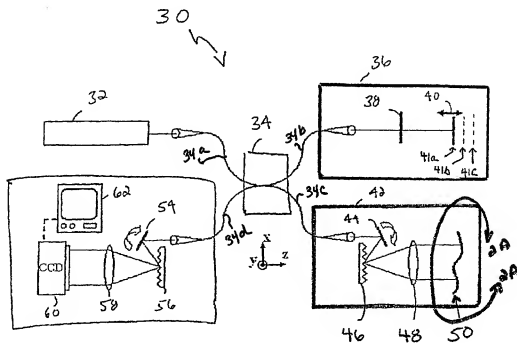
(57) Abstract: A method and apparatus for obtaining three-dimensional surface measurements using phase-sensitive spectrally encoded imaging is described. Both transverse and depth information is transmitted through a single-mode optical fiber, allowing this technique to be incorporated into a miniature probe.

METHOD AND APPARATUS FOR THREE-
DIMENSIONAL SPECTRALLY ENCODED IMAGING

FIELD OF THE INVENTION

5   This invention relates generally optical imaging and more particularly to a method
and apparatus for performing three-dimensional surface measurements.

BACKGROUND OF THE INVENTION

As is known in the art, optical techniques for surface profilometry are commonly
10   performed using interferometric measurements. Analyzing the interference fringe pattern
formed by overlap of a reflected wave from an optically smooth surface with a reference
wave, enables surface profile measurements with high accuracy. Projecting an interference
fringe pattern on an object surface is effective for probing rough surfaces. High-resolution,
point-by-point measurements of rough surfaces have been demonstrated using a long
15   coherence length source with a Fizeau interferometer and with a broadband source.

White-light interferometry is capable of simultaneously imaging large field of views
by scanning only the path length of a reference arm. In this approach, light reflected from
the surface interferes with a reference wave to form a speckle pattern on a camera. When the
20   reference optical path length is scanned, each individual speckle exhibits an intensity
modulation. The surface height is determined at the maximum point of the modulation
envelope. White-light interferometry is an extremely robust technique, allowing for high
resolution imaging in three dimensions with a large field of view.

25   Depth resolved imaging with a large, three-dimensional field of view is more
challenging when utilizing small diameter flexible imaging probes such as borescopes,
laparoscopes, and endoscopes. Confocal imaging through a fiber-bundle using a lens with a
high numerical aperture is one solution to this problem. The three-dimensional field of view
for these devices, however, is limited to less than a few millimeters due to the small
30   objective lens clear aperture and low f-number required for high-resolution optical
sectioning.

Other methods, such as stereo imaging and structured illumination have been proposed. These methods all require additional hardware for the probe, increasing the size, cost, and complexity of these devices.

5   SUMMARY OF THE INVENTION

In accordance with the present invention, an imaging technique includes encoding a transverse location of an object by wavelength and encoding an axial or depth coordinate of each point on the object by phase. With this particular arrangement, a technique for generating two-dimensional images of an object as well as surface profile measurements of
10   the object is provided. By combining the surface profile with the two dimensional image, a three-dimensional spectrally-encoded imaging technique is provided. Encoding the depth (or height) information is accomplished by changing a phase length of a reference path and detecting phase differences in signals reflected from the surface of the object each time the phase length of the reference path is changed.. The phase length of the reference path
15   establishes a coherence length (CL) at the surface being measured. Thus by changing the phase length of the reference path, a different coherent length is established. By detecting phase differences in signals reflected from the surface of the object each time the phase length of the reference path is changed, the height at different points along the surface can be detected.

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In one embodiment, a surface profile of an object is measured by utilizing the technique of the present invention in conjunction with a probe of the type described in published PCT application number WO 02/038040 A2 (now pending in the U.S. Patent and Trademark Office as application no. 09/709,162 filed November 10, 2000) said application
25   being assigned to the assignee of the present invention. The techniques of the present invention can thus be used in conjunction with techniques for performing a miniature endoscopy with a high number of resolvable points as described in the aforementioned U.S. Application no. 09/709,162. The aforementioned U.S. Application no. 09/709,162 describes a technique in which a broadband light source and a diffraction grating are used to spectrally
30   encode reflectance across a transverse line within a sample and a two-dimensional image is formed by scanning this spectrally encoded line. Since this method only requires a single

optical fiber, it is capable of enabling two-dimensional imaging through a small diameter, flexible probe. By utilizing the techniques of the present invention, a three-dimensional spectrally-encoded image can be provided. In three-dimensional spectrally-encoded imaging, the transverse location of the image is encoded by wavelength and the axial or depth coordinate of each point is encoded by phase.

Using the phase-sensitive spectrally encoded imaging techniques of the present invention, volume data can be acquired through a single optical fiber. The present invention thus makes possible three-dimensional macroscopic imaging within the confines of a miniature, flexible probe. Data measured using techniques of the present invention has clearly demonstrated the potential of this technology for probe-based imaging for industrial applications. It should be appreciated, however, that the phase-sensitive spectrally encoded imaging technique of the present invention can also be used in medical and other applications. For example, phase-sensitive spectrally encoded imaging technique of the present invention can be used to visualize multiply scattering tissues in three-dimensions for biomedical applications.

In accordance with a further aspect of the present invention, a method for measuring a surface of a specimen includes operating a beam provided as spectrally-encoded points of a spectrum, focusing the beam onto a specimen disposed in a sample arm, scanning the beam in a first direction across the specimen to create a two dimensional image, changing a path length of a reference path and generating an interference pattern with a reflection from light from the sample and reference arms. The signals from the sample and reference arms are then directed to a detection arm where they are combined. With this particular arrangement, a method for detecting a height of a surface is provided. In order to obtain a surface profile of the specimen, the propagation path length of the reference path is changed and interference patterns at each changed path length are used to provide the height information.

In accordance with a still further aspect of the present invention, a system includes a source, a splitter/combiner having a first port coupled to the source, having a second port coupled to a reference path, having a third port coupled to a sample path and having a fourth

port coupled to a detection path. The sample path includes a dispersive element which provides a spectrally encoded focal plane. The reference path includes a path length change device which is adapted to change a propagation path length of light propagating in the reference path. With this particular arrangement, system for three-dimensional imaging is

5   provided. By changing the propagation path length of the reference path, a phase-sensitive spectrally encoded imaging system is provided. The phase information contained in signals reflected form the specimen in the sample path can be used to provide depth (height) information of a surface. Thus, both transverse and depth information can be transmitted through a single-mode optical fiber, allowing such a system to be incorporated into a

10   miniature probe.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing features of this invention, as well as the invention itself, may be more fully understood from the following description of the drawings in which:

15   FIG. 1 is a block diagram of an apparatus for three-dimensional spectrally encoded imaging;

FIG. 2 is a schematic diagram of an exemplary embodiment of an apparatus for three-dimensional spectrally encoded imaging;

FIG. 2A is an enlarged view of the sample in FIG. 2 taken around lines 2A-2A in

20   FIG. 2;

FIG. 2B is a plot of an interference pattern provided from the system of FIG. 2;

FIG. 2C is a plot of a measured surface profile;

FIG. 3A is an image of a doll's face obtained using white light illumination and a charge coupled device (CCD) camera;

25   FIG. 3B is a conventional spectrally encoded-two-dimensional image of a doll's face obtained by blocking a reference arm in the system of FIG 2;

FIG. 3C is a gray scale image which shows a surface height obtained by determining the location of a maximum speckle intensity difference along an axial (z) axis;

FIG. 3D. is a doll's face represented by surface 3-D rendering;

30   FIG. 4A is plot of sagital (y-z) section from a data set;

FIG. 4B is a plot of a doll's actual profile; and

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FIG. 5 is a flow diagram which illustrates an exemplary technique for three-dimensional spectrally encoded imaging.

DETAILED DESCRIPTION OF THE INVENTION

5   Referring now to FIG. 1, a three-dimensional spectrally encoded imaging system 10 includes a source 12 coupled to a beam splitter 14 at first port 14a. It should be appreciated that beam splitter 14 may be implement using any techniques now known or later discovered. For example, splitter 14 may be provided as a fiber optic beam splitter, a free space splitter or a glass plate splitter.

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The system 10 includes a reference path 16 coupled to a second port 14b of the beam splitter 14 and a sample path 18 coupled to a third port 14c of the beam splitter 14. The reference path 16 includes a path-length change device 17. Path-length change device 17 is adapted to change a propagation path length of light propagating in the reference path 16.

15   The device 17 allows the optical path length of the reference arm 17 to be changed in a controlled and known manner. In some embodiments, device 17 may be provided such that it can introduce a change in the group delay of optical signals propagating in path 16. Such a change in group delay may or may not be accompanied by a physical change in the optical path length of the reference arm. Changes in group delay in optical signals may be desired to

20   reduce speckle artifacts and possibly result in increased system sensitivity. It should be appreciated that in embodiments in which the reference arm does not include a path-length change device 17, then the depth at a single spot along a scan line of a sample may be computed.

25   The sample path 18 has disposed therein a sample 19 (also referred to herein as a specimen 19). The sample path 18 may optionally include one or more of a dispersive elements 18a, a beam focusing device 18b and a scanning element (or more simply, a scanner) 18c as described in co-pending application no. 09/709,162. The dispersive element may be provided, for example, as a diffraction grating and in response to a signal fed thereto

30   from the beam splitter, the dispersive element disperses the signal into a spectrum in an image plane. The dispersive element may also be provided as a dispersive prism, a fiber

grating, a blazed grating, a grism, a holographic lens grating or any other element which provides angular separation of light signals propagating at different wavelengths. That is, in response to light signals incident thereon, the dispersive element directs different wavelengths in different directions or, stated differently, the dispersive element disperses the spectrum of the light signal provided thereto to provide a spectrally encoded focal plane.

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The beam focusing device 18b focuses individual spectrally-encoded points toward the sample 19 disposed in the sample path 18. The beam focusing device may be provided, for example, from an optical system such as a lens system.

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The scanning element 18c, scans the spectrally-encoded beam across the specimen 19 to produce a two-dimensional image. It should be understood that the positions of the dispersive device 18a and beam focusing device 18b are selected in accordance with the requirements and needs of the particular application.

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It should be appreciated that in some embodiments, it may be desirable to provide the dispersive element 18a the scanner 18c and the beam focusing device 18b as separate elements. For example, the dispersive element 18a may be provided as a diffraction grating, the beam focusing device 18b may be provided as a lens disposed to focus the beam on the

20   specimen and the scanner 18c may be provided as a galvanometric scanner disposed to direct light to and from the diffraction grating. The dispersive element 18a, scanner 18c and lens system 18b may be combined in a single housing.

In other embodiments, however, it may be desirable to provide the dispersive element

25   18a, the scanner 18c and the lens system 18b as a single integrated element. Alternatively still, the functions performed by the dispersive element 18a, scanner 18c and lens system 18b may be provided from a single device.

In order to obtain a surface profile of the specimen 19, the propagation path length of

30   the reference path 16 is changed. In one embodiment, the path length of the reference path 16 is changed by providing the device 17 as a movable reflective device disposed at the end

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of the reference arm. Movement of the reflective device changes the path length of the reference arm 16. In one embodiment, the movable reflective device can be provided as a mirror disposed on a movable platform at the end of the reference arm 16. Movement of the platform (and thus the mirror) changes the optical path length of the reference arm 16. Other

5   techniques for changing the path length of the reference path, may of course, also be used.

The source 12 emits a light signal to the beam splitter 14 which splits the light and provides a first portion of the light signal to the reference arm 16 and a second portion of the signal to the sample arm 18. The light impinges upon device 17 and sample 19 in the

10   reference and sample paths 16, 18 respectively and is reflected back toward ports 14b, 14c of splitter/combiner 14. Ideally, the splitting ratio of the splitter/combiner 14 is selected such that an equal amount of reflected power is received at each of the splitter ports 14b, 14c.

The reference line can also include an optical attenuator (not shown in FIG. 1) having

15   an attenuation setting selected to adjust the strength of a reference beam reflected from a reflective device to increase (and in some cases maximize) the contrast of an interference pattern generated from the reflected reference beam and the reflected beam from the sample arm.

20   Signals reflected from the reference and sample arms 16, 18 are coupled to a detector arm 20 via splitter/combiner circuit 14. The detector arm 20 receives signals fed thereto and detects depth. As mentioned above, it is possible for detector arm 21 to analyze a pattern provided thereto without scanning the reference arm. Detector 21b can thus determine depth information at a single point in an image, along a line in an image or in an entire two-

25   dimensional image (i.e. to provide a three-dimensional image).

In one embodiment, the detector receives time-domain measurements and provides depth information by using a Fourier transform (e.g. an FFT). In another embodiment, detector arm 21 includes a dispersive device 21a and a detector 21b. In this case, the

30   dispersive element disperses the wavelengths of an optical signal provided thereto and the dispersed spectrum is detected by the detector 21b. The dispersive device 21a may be

provided from a number of devices including but not limited to a grating or a dispersive prism. Similarly, the detector 21b may be provided from a number of devices including but not limited to a charge coupled device (CDD) camera.

5   Referring now to FIG. 2, a system 30 for performing three-dimensional spectrally encoded imaging includes a source 32 having a relatively broad bandwidth coupled to a single mode fiberoptic interferometer 34 at first port 34a. A reference path 36 is coupled to a second port 34b of the interferometer 34, a sample path 42 is coupled to a third port 34c of the interferometer 34 and a detection path 52 is coupled to a fourth port 34d of the 10   interferometer 34.

          In one embodiment, the source 32 is provided as a broad-bandwidth titanium-sapphire source having a center wavelength of 860 nanometers (nm) and an FWHM bandwidth of 200 nm while the interferometer 34 is provided as a 50/50 Michelson 15   interferometer and the sample arm 42 includes a diffraction grating (600 lines/mm) to disperse the spectrum in the horizontal image plane (x-axis). A lens 48 (f = 75 mm, beam diameter = 1 mm) focuses the individual spectrally-encoded points onto a specimen 50.

          The beam was scanned in the vertical dimension (y-axis) by a galvanometric scanner 20   (60 Hz) 44 to create a two-dimensional image. These parameters resulted in a spatial transverse resolution of approximately 40 μm. The image was comprised of approximately 585 x 585 resolvable points; each transverse spot contained a bandwidth of 0.34 nm. The overall power on the sample was 10 mW.

25   In order to obtain surface profiles, the path length of the reference arm 36 was controlled by moving a mirror 40 mounted on a translation stage. The power of the reference beam was attenuated using a neutral density (ND) filter 308 to maximize the contrast of the interference pattern.

30   Referring now to FIGs. 2 and 2A, by placing the mirror in a first location 41a, the reference arm is provided having a first path length. This path length results in a first

coherence length (CL) 41a. Reflections from the surface of the sample 50 at this coherence length represent a first depth. When the mirror is moved to a second location 41b, the reference arm is provided having a second path length in this example, the second reference arm path length is longer than the first reference arm path length. This path length results in

5   a second coherence length (CL) 41b. Reflections from the surface of the sample 50 at this second coherence length represent a second depth. Similarly, when the mirror is moved to a third location 41c, the reference arm is provided having a third path length in this example, the third reference arm path length is longer than the first and second reference arm path lengths. The third path length results in a third coherence length (CL) 41c. Reflections from

10   the surface of the sample 50 at this second coherence length represent a third depth. In this manner, the depth information of the surface sample is provided.

Although this example utilizes only three coherence lengths, it should be appreciated that the any desired number of coherence lengths can be used. The particular number of

15   coherence lengths to use will depend upon the particular application. Its should also be appreciated that while the coherence lengths are changed by moving a mirror to adjust a phase length of the reference path, any technique which effectively changes the coherence length such that phase can be used to determine surface depth of a sample can also be used.

20   Referring again to FIG. 2, at the detection path 52, the signals from the sample and reference arms are combined and detection is performed. In one embodiment, the fields from the sample and reference arms 36, 42 were combined and spatially dispersed by a diffraction grating 56 (600 lines/mm) and a lens 58 (f = 60 mm) onto a charge-coupled device (CCD) array 60. It should be appreciated that the focusing function provided by lens

25   58 could also be provided at the output of the combiner (i.e. output 34d) or at the input to the detector arm. For example, if a fiber optic cable were used to couple interferometer 34 to detector 52, then the focusing function could be accomplished at the detector end the of fiber optic cable. Vertical scanning was performed by another galvanometric scanner 54 which was synchronized with the sample arm y-axis scanner. The resulting interference pattern

30   was viewed on a display 62 (e.g. a monitor) in real time, digitized, and stored.

At each horizontal line on the CCD, the intensity is given by:

$$I(\omega) = \left|E(\omega) + E_0(\omega)\right|^2 = 2\left|A_0(\omega)\right|^2 \cdot \left\{1 - \cos\left[\phi(\omega) - \phi_0(\omega)\right]\right\}, \tag{1}$$

where $E(\omega) = A(\omega)\exp\left(i\phi(\omega)\right)$ and $E_0(\omega) = A_0(\omega)\exp\left(i\phi_0(\omega)\right)$ are the spectra reflected from the sample and the reference arms, respectively. For simplicity, it is assumed that the spectral amplitudes from sample and reference arms are real and equal, $A(\omega) = A_0(\omega)$. Algorithms for extracting phase difference from a spectral interference signal between two waves with continuous and smooth phases are well known. Spectral phase measurements were performed mainly for dispersion measurements using broadband sources and white light. Using a Fourier-limited reference field ($\phi_0(\omega) = 0$) with a given delay τ between the reference and the signal fields, the interference term in Eq. (1) is simply $\cos\left[\phi(\omega) - \omega\tau\right]$. With a straight forward algorithm, the spectral phase can be unambiguously extracted from the interference pattern $I(\omega)$. In one configuration, the depth or surface height h at each point is given by $h = c \cdot \phi(\omega)/(2\omega)$, where c is the speed of light.

To demonstrate the ability of this scheme to probe optically smooth surfaces, a plano-convex lens (Melles-Griot, f = 1 m, BK7 glass) was placed in the sample arm (e.g. lens 48 was provided as a plano-convex lens), with its convex surface facing toward the grating. In order to match the optical path length over the entire field of view, an additional two lenses, in a confocal configuration, were placed at the sample arm between the scanner and the diffraction grating. A delay of 2.18 ps (654 μm) was introduced between the sample and the reference arms. The interference pattern for this setup is shown in Fig. 2B. The surface profile was obtained using the algorithm described in "Linear techniques of phase measurement by femtosecond spectral interferometry for applications in spectroscopy," J. Opt. Soc. Am. B 12, 2467 (1995) L. Lepetit, G. Chériaux, and M. Joffre. FIG. 2A is a two-dimensional spectrally-encoded interferogram provided from the curved surface of a lens (f = 1 m).

Referring Now to Fig. 2C, a measured surface profile along a horizontal line is plotted as a solid line 66 in Fig. 2C. For comparison, the spherical curve of the lens's radius, calculated according to $R = f \cdot (n-1)$, ($n = 1.5187$), is plotted as a dashed line 68 (Fig. 2C).

FIG. 2C thus illustrates that the profile of the lens (solid line 66) measured using the described system agrees with a calculated profile (dashed line 68). The differences between the measured and the calculated profiles can be attributed to the loss of fringe contrast on the right side of the frame and due to low fringe density on the left side. When the sample contains steep local slopes, the fringe pattern became too dense to be resolved by the imaging system. This limitation prevented the system from measuring optically smooth surfaces with slopes greater than λ / d, where λ is the wavelength and d is the transverse spot size.

In most industrial and medical applications, the specimen surface is not optically smooth, but contains many surface irregularities. When the surface is rough and the diffraction-limited point-spread function of the imaging system is broad in comparison to the microscopic surface variations, the interference between the sample and the reference is manifested by a granular speckle pattern. This pattern has a characteristic speckle size that matches the system's point-spread function. The depth of the speckle pattern along the z axis is defined by the coherence length,

$$CL = (c \bullet N) / \Delta\omega \qquad\qquad (2)$$

where N is the number of resolvable points along the x-axis (wavelength) and $\Delta\omega$ is the total source bandwidth. Unlike white-light interferometry, where the coherence length is given by $CL = c / \Delta\omega$ and can be as short as a few microns, here the coherence length is N times larger, since it is determined only by the spectral width of each spectrally encoded spot. Throughout this work, the coherence length (310 µm) was smaller than the confocal parameter (2.7 mm) and therefore determined the axial resolution. The large depth of focus allowed imaging over a range equivalent to the confocal parameter by scanning only the optical path length of the reference arm.

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To demonstrate the ability of a 3-D spectrally-encoded imaging apparatus to measure the profile of rough surfaces, the face of a small plastic doll was imaged. The doll's face is shown in Fig. 3A. The image of the doll's face in Fig. 3A was obtained using white light illumination and a standard CCD camera. It should be noted that the scale bar in FIG. 3A

5   represents 4 mm while the scale bars in FIGs. 3B – 3D represent 1 mm.

In FIG. 3B, the standard spectrally encoded-two-dimensional image is shown. The surface height, measured by 3D spectrally encoded imaging, is represented as a gray scale image, where z values closer to the probe have a higher pixel intensity. This image is

10   obtained by blocking a reference arm in the system of FIG. 2. When the light returned from the reference arm was allowed to interfere with that of the sample arm, a speckle pattern was observed in portions of the image. A full three-dimensional data set was acquired by capturing 45 frames as the reference arm path length was scanned in steps of 100 μm. The natural logarithm of the absolute value of the difference between consecutive frames was

15   calculated, followed by moderate volumetric smoothing (kernel = 3x3x3 pixels). The surface height was obtained by determining the location of the maximum speckle intensity difference along the axial (z) axis (displayed as a gray scale image in Figure 3C). FIG. 3D corresponds to a surface rendering of the dolls face using the data shown in Fig. 3C.

20   Referring now to FIGs. 4A and 4B, for estimating the experimental depth resolution a sagital (y-z) section was plotted (Fig. 4A) from the data. The sagital section was placed next to the actual doll's profile (Fig. 4B). The measurement revealed an axial resolution of approximately 330 μm (FWHM of the coherence envelope), which is in reasonable agreement with the predicted axial resolution of 310 μm. The scale bar (visible in Fig. 4B) is

25   1mm.

Three dimensional (3-D) spectrally-encoded imaging can be used in many configurations to suit specific applications. For example, this method is capable of measuring a surface within a volume of 50x50x30 millimeters (x, y, z respectively) with,

30   typically, 200x200x280 resolution points (250 μm transverse spot-size and 107 μm axial resolution). Using a CCD camera (10,000 frames per second) and a rapidly scanning optical

delay line in the reference arm the three-dimensional data set could be captured and displayed in real time (30 frames per second).

        Referring now to Fig. 5, a technique for producing a three-dimensional image begins
5.   by illuminating a line on a sample and then scanning a reference line as shown in processing blocks 70, 72. Next, the depth information is determined as shown in block 74. In one embodiment, this is achieved by measuring the number of fringes within a spot on the sample (e.g. analyzing the number of fringes using a fast Fourier Transform(FFT) or other technique) and translating this information to depth information. As shown in decision block
10   76, if there are no more lines on the sample to detect, then processing ends. Otherwise a next line on the sample is selected and illuminated as shown in blocks 78, 80 and blocks 72-78 are repeated until the imaging process is complete.

        In summary the techniques and apparatus described above can be used to provide
15   three-dimensional macroscopic images using a phase-sensitive spectrally encoded imaging technique. Using the techniques of the present invention, volume data can be acquired through a single optical fiber without any additional modifications to the spectrally-encoded imaging device. These features make three-dimensional imaging within the confines of a miniature, flexible probe possible.
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        Although only a few exemplary embodiments of this invention have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended
25   to be included within the scope of this invention as defined in the following claims. It should further be noted that any patents, patent applications and publications referred to herein are incorporated by reference in their entirety.

        What is claimed is:

CLAIMS

1 1.   A method for three-dimensional imaging of a surface comprises:
2   encoding a wavelength to determine a transverse location of the surface; and
3   encoding a phase to determine a depth coordinate of at least one point on the
4 surface.

1 2.   The method of Claim 1 wherein encoding a phase to determine a depth coordinate
2 of at least one point on the surface comprises:
3   transmitting a signal against the surface and to a reference path having a first
4 phase length;
5   collecting a phase coherent signal reflected from the surface;
6   collecting a phase coherent signal from reference path having the first phase
7 length;
8   detecting an interference signal produced by interference between a phase of the
9 coherent signal collected from the surface and a phase of the reference signal from the
10 reference path having the first phase length; and
11   processing the interference signal to determine depth information of the surface.

1 3.   The method of Claim 2 further comprising:
2   changing the phase length of the reference path to a second phase length;
3   collecting a phase coherent signal from reference path having the second phase
4 length;
5   detecting an interference signal produced by interference between a phase of the
6 coherent signal collected from the surface and a phase of the reference signal from the
7 reference path having the second phase length; and
8   processing the interference signal to determine depth information of the surface.

1 4.   The method of Claim 2 further comprising:
2   repeatedly changing the phase length of the reference path to a plurality of
3 different phase lengths;

4   collecting phase coherent signals from reference path at each of the different

5   phase lengths;

6   at each of the different reference path phase lengths, detecting an interference

7   signal produced by interference between a phase of the coherent signal collected from the

8   surface and a phase of the reference signal from the reference path; and

9   processing each interference signal to determine depth information of the surface.

1   5.   A method for three-dimensional surface measurements of an object comprising:

2   (a)   determining a transverse location of a surface of a sample by encoding a

3   wavelength;

4   (b)   determining a depth coordinate of at least one point on the surface by encoding a

5   phase.

1   6.   The method of Claim 5 wherein determining a depth coordinate of at least one

2   point on the surface by encoding a phase comprises measuring an interference signal

3   produced by interference between a phase of a reference signal and a phase of a signal

4   reflected from a surface of the object.

1   7.   The method of Claim 6 further comprising providing the reference signal having a

2   plurality of different phases and using the different reference signal phases to determine

3   height at a plurality of locations on the surface.

1   8.   A method for measuring a surface of a specimen, the method comprising:

2   (a)   operating a beam provided as spectrally-encoded points of a spectrum;

3   (b)   focusing the beam onto a specimen disposed in a sample arm;

4   (c)   scanning the beam in a first direction across the specimen to create a two

5   dimensional image;

6   (d)   changing a path length of a reference path; and

7   (e)   generating an interference pattern with a reflection from light from the sample and

8   reference arms;

9   (f)   directing the signals from the sample and reference arms to a detection arm; and

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10 (g)   combining the signals from the sample and reference arms at the detection arm.

1   9.   The method of Claim 8 wherein changing a path length of a reference arm

2   comprises moving a reflective surface in the reference arm.

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1   10.   The method of Claim 8 wherein changing a path length of a reference arm

2   comprises moving a mirror in a direction which is the same as the direction of light

3   propagation in the reference path.

1   11.   The method of Claim 8 wherein combining the signals from the sample and

2   reference arms at the detection arm comprises combining and spatially dispersing the

3   signals with a dispersive element.

1   12.   The method of Claim 11 further comprising focusing the dispersed signals onto an

2   imaging system.

1   13.   The method of Claim 12 further wherein focusing the dispersed signals onto an

2   imaging system comprises focusing the dispersed signals with a lens onto a charge-

3   coupled device.

1   14.   A system for three-dimensional imaging of a surface comprises:

2   means for encoding a wavelength to determine a transverse location of the

3   surface; and

4   means for encoding a phase to determine a depth coordinate of at least one point

5   on the surface.

1   15.   The method of Claim 14 wherein said means for encoding a phase to determine a

2   depth coordinate of at least one point on the surface comprises:

3   a source for transmitting a signal against the surface and to a reference path

4   having a first phase length;

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5   means for collecting a phase coherent signal reflected from the surface;

6   means for collecting a phase coherent signal from the reference path having the

7 first phase length;

8   means for detecting a phase of the coherent signal collected from the surface and

9 a phase of the reference signal from the reference path having the first phase length; and

10   means for processing the phase of the coherent signal collected from the surface

11 and the phase of the reference signal to determine depth information of the surface.

1 16.   The method of Claim 2 further comprising:

2   changing the phase length of the reference path to a second phase length;

3   collecting a phase coherent signal from reference path having the second phase

4 length;

5   detecting an interference signal produced by interference between a phase of the

6 coherent signal collected from the surface and a phase of the reference signal from the

7 reference path having the second phase length; and

8   processing the interference signal to determine depth information of the surface.

1 17.   The system method of Claim 16 further comprising means for changing the phase

2 length of the reference path to a plurality of different phase lengths.
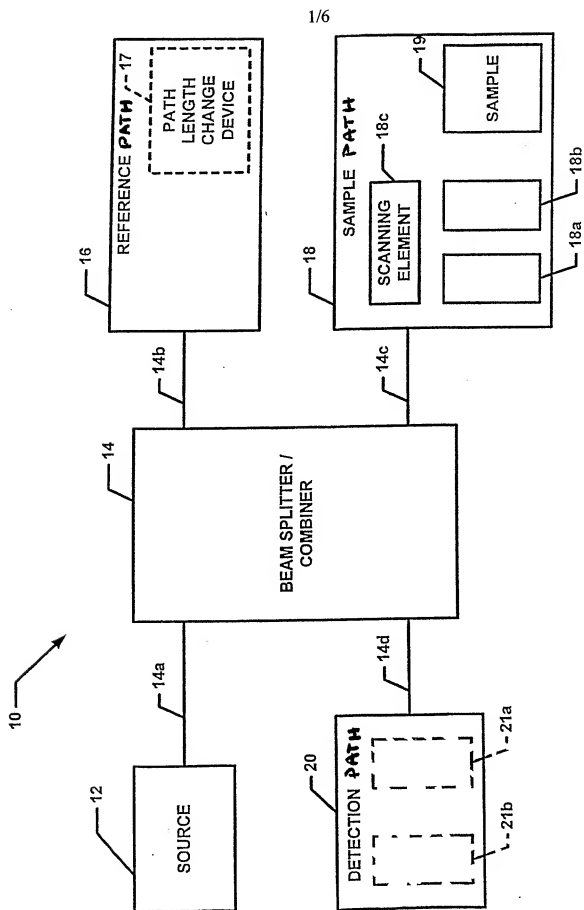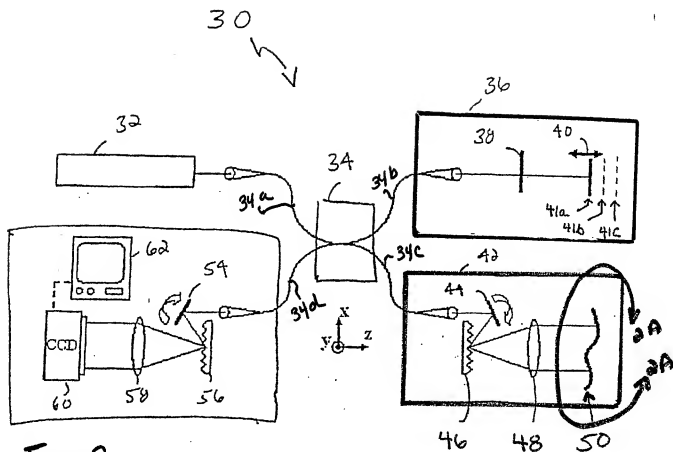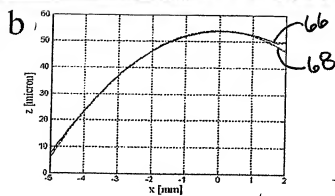
FIG. 1

Fig. 2

Fig. 2A
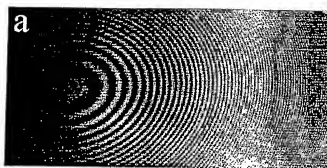
FIG. 2 B

a

b

FIG. 2 C

FIG. 3A   FIG. 3B
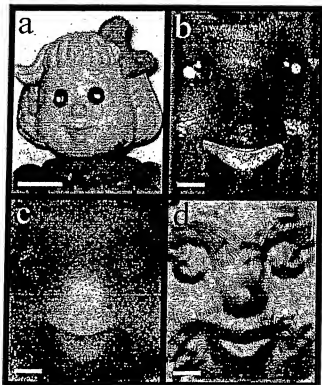
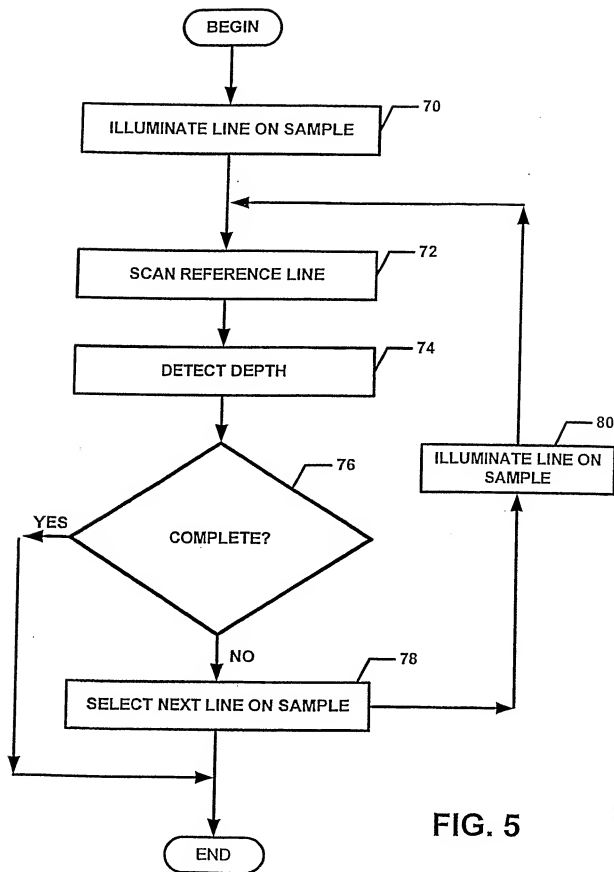FIG. 3C   FIG. 3D
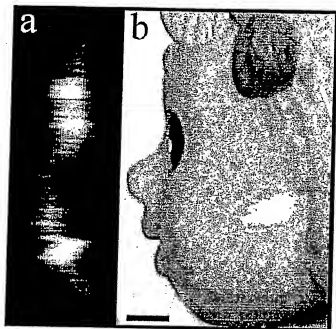
FIG. 4A   FIG. 4B

FIG. 5

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   G01B11/24   G01B11/25   G01B11/30   G01B9/02   A61B1/07

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   G01B   A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 99/44089 A (THE GENERAL HOSPITAL CORPORATION; WEBB, ROBERT, H; TEARNEY, GUILLERMO,) 2 September 1999 (1999-09-02) page 3, line 10 - page 4, line 7 page 4, line 29 - page 5, line 16 page 5, line 27 - page 6, line 12 abstract;- figures 1,2,4,5a	1-17
X	WO 03/062802 A (THE GENERAL HOSPITAL CORPORATION; DE BOER, JOHANNES, FITZGERALD; TEARN) 31 July 2003 (2003-07-31) page 2, line 14 - line 19 page 7, line 4 - line 18 page 13, line 1 - page 17, line 20 abstract; figures 1-3	1-17

-/--

| X | Further documents are listed in the continuation of box C. | | X | Patent family members are listed in annex. |

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Date of the actual completion of the international search	Date of mailing of the international search report
3 May 2005	11/05/2005

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 95/33971 A (MASSACHUSETTS INSTITUTE OF TECHNOLOGY) 14 December 1995 (1995-12-14) page 9, line 23 – page 14, line 34 abstract; figures 2,3,5	1–17

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